Highlights in particle physics

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In the absence (or mere presence) of outstanding highlights in the latest results of high energy physics experiments, I have chosen to explore what enters in two out of the most famous (but complicated) plots of our field: the so-called blueband plot highlighting the most probable mass of the Standard Model Higgs boson as indicated by the electroweak precision measurements mostly performed at LEP and the global fit of the Standard Model Cabibbo-Kobayashi-Maskawa (CKM) matrix parameters to the B-factories and Tevatron recent data. In the discussion of the huge amount of data feeding these synthesis figures, a selection of the most recent and appealing results connected to these subjects will be described.

1 Introduction

At the time of the proposal of this seminar, the model of a High Energy Physics summer conference review sounded a good approach to cover the present questionning of the particle physics while discussing the grounds of our field. It happened that the title was at least badly chosen, the Standard Model (SM)[1] being awarded its latest trophees, as testified by the Nobel Prize 2008 given to Kobayashi and Maskawa for their pioneering work in the description of flavour transitions [2] within the SM, which has been proven throughout the last decade to be realized in Nature at the level of precision achieved by the B-factories. This will be discussed in the second part of this summary. The first part will be devoted to the scrutiny of the electroweak precision measurements performed by the LEP, SLD and Tevatron experiments [4] which, simultaneously analyzed in the framework of the SM, yield a constraint on the mass of the only experimentally missing field of the Model : the Brout-Englert-Higgs boson [3].

2 Electroweak precision measurements

Figure 1 shows the whole set of electroweak precision measurements performed at LEP and SLD experiments together with their deviation to the SM prediction [4]. A fair agreement is observed. It is necessary that radiative corrections are embedded in the calculation such that the data are accomodated. For instance, the SM $Z \to b\bar{b}$ partial width, denoted R_b, is 0.2184 at the Born order [a] while the measurement reads $R_b = 0.21629 \pm 0.00066$. In that case, the relevant radiative corrections take place at $Zb\bar{b}$ vertex and mostly involve the top quark yielding an indirect determination of its mass in perfect agreement with the direct measurement. Other

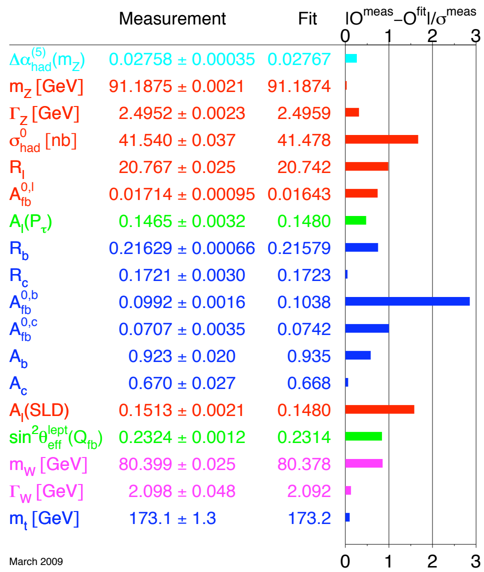

Figure 1: All the relevant electroweak precision measurements and their SM predictions. The departure of the measurement with respect to its prediction is given.

observables such as the LR or the forward-backward asymmetries at the Z pole are exhibiting radiative corrections at the Z propagator, which do not imply solely the top quark but also the Higgs boson (through a logarithmic mass dependence yet). Hence, a global analysis of all these observables gives a constraint of the free parameters of the SM and singularly on the mass of the Higgs boson (M_H), which escaped so far the direct search. The result of this global fit is shown in the Figure 2 together with a lower limit issued from the direct searches. The preferred value is around 90 GeV/c^2 and an upper limit at 95% Confidence Level (CL) can be derived:

$$M_H < 163 \text{ GeV/c}^2. \tag{1}$$

2.1 The Tevatron results

In the recent times, significant progresses have been made uniquely due to the Tevatron experiments (The LHC experiments are still waiting for their first data). This is true for the

[a] See Sebastien Descotes-Genon's lecture for the details of these calculations.

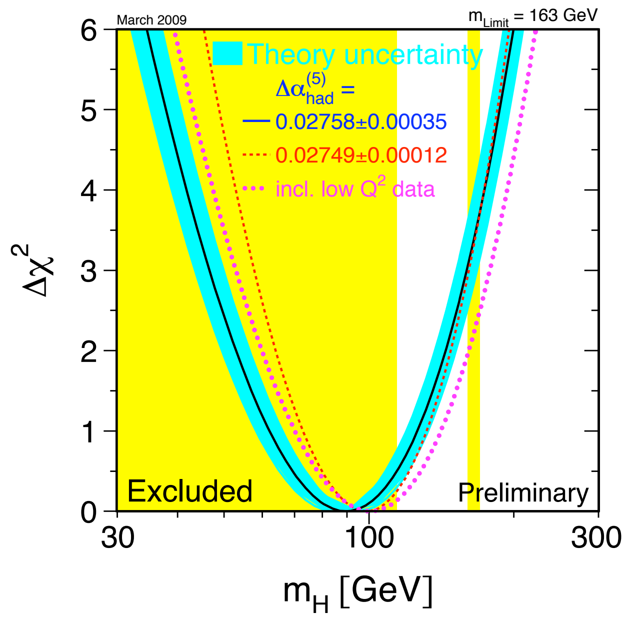

Figure 2: $\Delta\chi^2$ probability distribution for the Higgs boson mass as given by the SM fit to the whole set of electroweak precision measurements.

increasingly precise measurements of the W (M_W) and the top-quark (m_t) masses, improving the indirect constraint on the Higgs mass as well as for the direct search [6].

The latest m_t and M_W measurements are taking benefit of the statistics recorded up to 2008 by the D0 and CDF experiments. As far as M_W is concerned, LEP and Tevatron are in satisfactory agreement. The top-quark mass measurement precision is limited by the systematic uncertainties [5]:

$$M_W = 80432 \pm 39 \text{ MeV/c}^2, \ m_t = 173.1 \pm 0.6 \text{ (stat.)} \pm 1.1 \text{ (syst.) GeV/c}^2. \tag{2}$$

The Higgs boson is searched for at Tevatron in a mass range up to 200 Gev/c^2 in several final states (fermionic or bosonic decays). But the most significant sensitivity is so far achieved in the decay mode $H \to WW$ hence selecting the region of preferred masses close to the kinematical threshold of 160 GeV/c^2. The Figure 3 shows the excluded Higgs mass regions at 95% CL. The Tevatron experiments added an additionnal exclusion for masses lying between 160 and 170 Gev/c^2.

3 Flavour Physics

Let's begin this section with few theoretical words. Once the electroweak symmetry is spontaneously broken, the lagrangian density which describes the charged current flavour transition between quarks reads as:

$$\mathcal{L}_W = i\frac{g_1}{\sqrt{2}}(\bar{U}_{Li}\gamma^\mu \mathcal{U}^u_{ik}\mathcal{U}^{d\dagger}_{kj}D_{Lj}{W_\mu}^+ \tag{3}$$

$$+ \ \bar{D}_{Li}\gamma^\mu \mathcal{U}^d_{ik}\mathcal{U}^{u\dagger}_{kj}U_{Lj}{W_\mu}^-) \,. \tag{4}$$

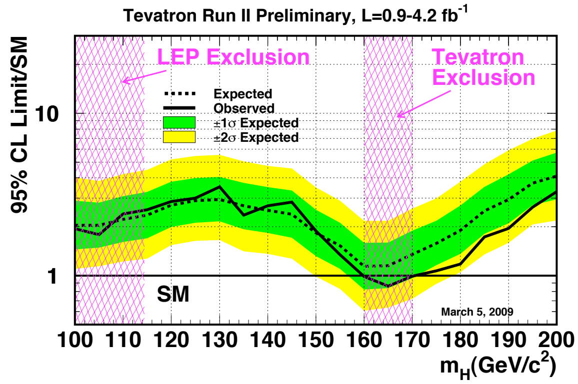

Figure 3: CL curve derived by the Tevatron experiments. There is an excluded band between 160 and 170 Gev/c^2 at 95% CL.

where g_1 denotes the weak coupling constant and γ^μ the Dirac matrices. $(U,D)_L^{I_3}$ are the left chirality doublets written in the basis of the weak eigenstates. The unitary matrices $\mathcal{U}_L^{u(d)}$ and $\mathcal{U}_L^{u(d)}$ do the change from the weak eigenstates to the mass eigenstates bases. Flavour Physics is hence another window and a complementary approach to study the electroweak symmetry breaking. The CKM matrix appears then naturally:

$$V_{CKM} = \mathcal{U}_L^u \mathcal{U}_L^{d\dagger} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} . \tag{5}$$

One can parametrize this 3×3 complex and unitary matrix by means of four parameters, inspired from [7]:

$$\lambda^2 = \frac{|V_{us}|^2}{|V_{ud}|^2 + |V_{us}|^2},\ A^2\lambda^4 = \frac{|V_{cb}|^2}{|V_{ud}|^2 + |V_{us}|^2},\ \bar{\rho} + i\bar{\eta} = -\frac{V_{ud}V_{ub}^*}{V_{cd}V_{cb}^*}. \tag{6}$$

The possibility of CP violation in the SM hence arises from a non-vanishing $\bar{\eta}$ value. The unitarity relations might be displayed elegantly in the complex plane by six triangles. One triangle (related to the physics of the B_d^0 meson) is particularly interesting because its sides have the same lengths ($\mathcal{O}(\lambda^3)$). Its apex is defined by the coordinates $(\bar{\rho}, \bar{\eta})$. The test of the KM mechanism hence consists in overconstraining the apex with redondant observables measuring the sides and the angles of the triangle.

3.1 Global fit and the consistency test of the KM mechanism

There are two kinds of observables which can be used to check the KM mechanism describing CP violation :

- the CP-violating observables, among which one obviously finds the three angles of the Unitarity Triangle (UT). The angle β is directly the phase of the neutral B^0 mesons mixing $B^0 - \bar{B}^0$ and is measured by constructing the time-dependent CP asymmetry between $B^0 \to J/\Psi K_S^0$ and $\bar{B}^0 \to J/\Psi K_S^0$ decay channels. The angle γ measurement makes use of the $B \to DK$ decays where the final state can be reached either through $b \to u$ or $b \to c$ transitions. The angle α measurement is obtained in the time-dependent analysis of the charmless decays $B^0 \to \pi\pi$, $B \to \rho\rho$ and $B \to \rho\pi$ which bring into play the

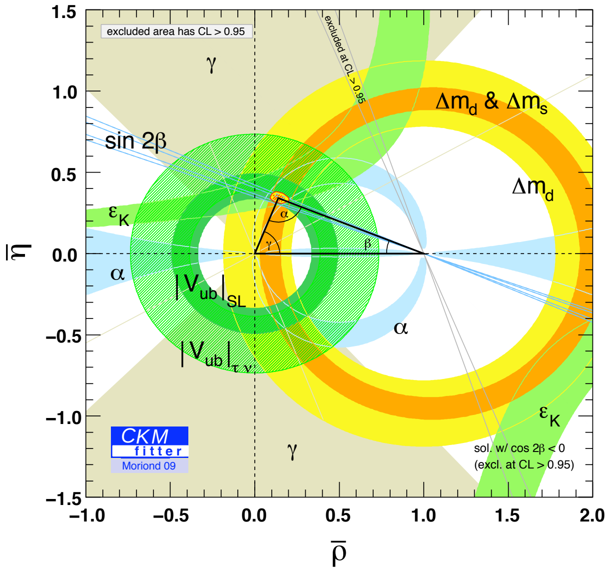

Figure 4: Constraint at 95 % Confidence Level (CL) in the $(\bar{\rho}, \bar{\eta})$ plane derived from the glbal fit of the SM parameters to the set of observables described in the text. Individual constraint are superimposed. The allowed region is circled in red - CKMfitter Group (2009).

interference between the mixing (depending on the weak mixing phase β) and the $b \to u$ decay (exhibiting γ). While the β measurement was the *raison d'être* of the B factories, the measurements of the α and γ angle were far more challenging. It is a tremendous success of the B factories to measure the α angle at the precision of few degrees which is achieved today [9]. Another CP-violating observable of interest is the measure of CP violation in the neutral kaons mixing, $|\epsilon_K|$. Though suffering from large QCD uncertainties, it is a valuable additional constraint and a way to get a consistency check that CP violation acts similarly in b-quark and s-quark sectors.

- The CP conserving observables which are actually measures of the sides of the angles. One finds there the CKM elements $|V_{ub}|$ and $|V_{cb}|$ derived from the branching ratios of b-hadron semileptonic decays, charmless and with charm, respectively. Powerful constraints are also derived from the measurement of the $B^0 - \bar{B}^0$ oscillation frequency, Δm_d. A joint analysis of Δm_d and its B_s meson analogue Δm_s allows to remove a part of the hadronic uncertainties plaguing their interpretation in the SM framework and provides a measure of the side of the triangle proportional to $|V_{td}|$.

All the constraints described above are displayed Figure 4. It is remarkable that a unique solution emerges, probing the KM mechanism to be at work to describe CP violation phenomena. One can further notice that CP-violating and CP-conserving observables define the same solution [8].

What could be the highlights in this standard landscape ? Let me distinguish two of them. The first one is somehow a surprise: the first evidence of $D^0 - \bar{D}^0$ mixing (which was initially thought so small that it could not be resolved by the current experiments) by at the B factories and the Tevatron simultaneously. I won't describe it in this document and point the interested reader to references [10]. The second is a hint of New Physics in the B_s meson mixing, experimentally explored since a couple of years thanks to the Tevatron experiments.

3.2 *Weak phase in B_s mixing*

The Tevatron experiments D0 and CDF have a wide program of flavour physics. The CDF experiment managed to resolve with an outstanding accuracy in 2006 the very fast oscillation frequency of the B_s mixing $\Delta m_s = (17.77 \pm 0.12)$ ps^{-1} [11]. This measurement was one of the highlight of year 2006. The next step in the exploration of the B_s sector is to measure the weak phase of the mixing $B_s^0 - \bar{B}_s^0$, denoted β_s, analogue of the β angle for the $B^0 - \bar{B}^0$ system. β_s is predicted very small in the framework of the SM, at the level of 1 but might be enhanced if New Physics contributions are realized in the $B_s^0 - \bar{B}_s^0$. It is searched for by reconstructing the B_s proper time of the final state $J/\Psi\phi$ and by building the corresponding CP asymmetry. The analysis is further complicated by the presence of two vector particles in the final state which require to perform an angular analysis to separate the CP eigenstates. The Figure 5 shows the combined constraint on $beta_s$ and $\Delta\Gamma_s$ (the lifetime difference between the light and heavy CP eigenstates) as determined by CDF and D0 experiments. This result is two standard deviations away from the SM prediction. Obviously, the precision is still modest and one should carefully conclude that more data are required. This measurement is one of the main target of the LHCb experiment where a precision of few degrees is expected for one nominal year of data taking.

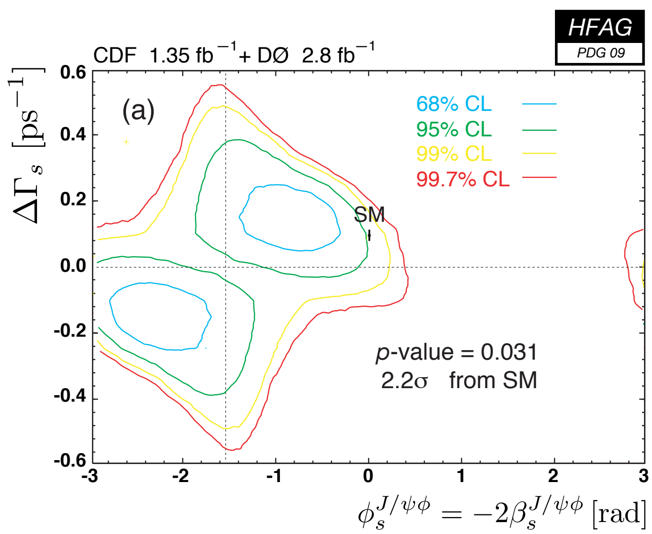

Figure 5: The excluded regions at 95 % CL in the space of parameters β_s and $\Delta\Gamma$ - CDF experiment (2006).

4 Conclusions

In the last two decades, the Standard Model of particle physics accumulated tremendous successes from the measurements at LEP, B factories and Tevatron experiments. All the measurements performed so far are in fair agreement with its predictions both in the gauge and flavour sectors of theory. As a counterpart, any model beyond the SM must accomodate the existing data (sometimes with a fantastic precision) which results in stringent constraints. Let's hope (and work for it!) that the Large Hadron Collider experiments will soon be in position to unravel the mystery of the electroweak symmetry breaking.

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References

1. S. Glashow, *Nucl. Phys.* **20** (1961) 579;
   S. Weinberg, *Phys. Rev. Lett.* **19**, 1264 (1967);
   A. Salam, in Elementary Particle Theory, ed. N. Svartholm (1968).
2. M. Kobayashi et K. Maskawa, *CP-Violation in the Renormalizable Theory of Weak Interaction.* Prog.Theor.Phys., **49** 652, (1973).
3. F. Englert and R. Brout, *Phys. Rev. Lett.* **13**, 321 (1964);
   P. Higgs, *Phys. Lett.* **B12** (1964) 132;
   P. Higgs, *Phys. Rev. Lett.* **13**, 508 (1964).
4. The ALEPH, DELPHI, L3 and OPAL Collaborations, the LEP Electroweak Working Group and the SLD Electroweak and Heavy Flavour Groups, *Precision Electroweak Measurements on the Z Resonance*, *Physics Reports*: Volume **427** Nos. 5-6 (May 2006) 257-454.
5. The CDF and D0 collaborations, [arXiv:hep-ex/0903.2503],
   The CDF and D0 collaborations, [arXiv:hep-ex/0808.0147].
6. The CDF and D0 collaborations, [arXiv:hep-ex/0903.4001].
7. L. Wolfenstein, *Phys. Rev. Lett.* **51**, 1945 (1983).
8. The CKMfitter Group (J. Charles *et al.*), *Eur. Phys. J.* **C41)** (2005) 1; updated in http://ckmfitter.in2p3.fr/.
9. For a nice and up-to-date review of the angle measurements, see K. Trabelsi's talk at the conference Hints of New Physics in Flavour Decays held in Tsukuba (2009). http://belle.kek.jp/hints09/program.html.
10. The BaBar collaboration, [arXiv:hep-ex/0703020],
    The Belle collaboration, [arXiv:hep-ex/0703036].
11. The CDF collaboration *Phys. Rev. Lett.* **97**, 242003 (1997).